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Can Gas prevent the Destruction of Thin Stellar Discs by Minor Mergers?

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ABSTRACT

We study the effect of dissipational gas physics on the vertical heating and thickening of disc galaxies during minor mergers. We produce a suite of minor merger simulations for Milky Way-like galaxies. This suite consists of collisionless simulations as well as hydrodynamical runs including a gaseous component in the galactic disc. We find that in dissipationless simulations minor mergers cause the scale height of the disc to increase by up to a factor of approximately two. When the presence of gas in the disc is taken into account this thickening is reduced by 25% (50%) for an initial disc gas fraction of 20% (40%), leading to a final scale height z_0 between 0.6 and 0.7 kpc (for a sech^2 profile), regardless of the initial scale height. We argue that the presence of gas reduces disc heating via two mechanisms: absorption of kinetic impact energy by the gas and/or formation of a new thin stellar disc that can cause heated stars to recontract towards the disc plane. We show that in our simulations most of the gas is consumed during the merger and thus the regrowth of a new thin disc has a negligible impact on the z_0 of the post merger galaxy. Final disc scale heights found in our simulations are in good agreement with studies of the vertical structure of spiral galaxies where the majority of the systems are found to have scale heights of 0.4 kpc $\lesssim z_0 \lesssim$ 0.8 kpc. We also found no tension between recent measurements of the scale height of the Milky Way thin disc and results coming from our hydrodynamical simulations. Even if the Milky Way did experience a recent 1:10 merger it is possible to reproduce the observed thin disc scale height, assuming that the disc contained at least 20% gas (similar to the gas fraction today) at the time of the merger. We conclude that the existence of a thin disc in the Milky Way and in external galaxies is not in obvious conflict with the predictions of the CDM model.

Key words: Galaxy: disc, evolution, structure – galaxies: disc, evolution, interactions, structure – methods: numerical, N-body simulation

1 INTRODUCTION

The cold dark matter (CDM) theory provides a successful framework for understanding structure formation in our Universe. Within this paradigm, dark matter first collapses in small haloes, which merge to form progressively larger haloes over time (e.g. White & Rees 1978; Davis et al. 1985). Major (near-equal mass) and minor (unequal mass) mergers are a generic feature of structure assembly in the CDM or hierarchical picture, and numerical simulations have shown that many of these merging structures survive within the virialized region of larger host haloes (e.g. Klypin et al. 1999; Reed et al. 2005; Diemand et al. 2008; Springel et al. 2008). These merger events are now widely believed to be responsible for shaping many galaxy properties. Major mergers play an important role in transforming disc-dominated spiral galaxies into spheroids (e.g. Hernquist 1993; Naab & Burkert 2003) and triggering episodes of enhanced star formation (SF) and active galactic nuclei (AGN) (Hernquist 1989; Barnes 1992; Mihos & Hernquist

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1994; Barnes & Hernquist 1996; Mihos & Hernquist 1996; Springel et al. 2005; Johansson et al. 2009). Minor mergers may explain the origin of thick discs (Abadi et al. 2003; Brook et al. 2004; Read et al. 2008; Kazantzidis et al. 2008), and the diffuse stellar halo around galaxies may be produced via tidal destruction of merging satellites (e.g. Bullock & Johnston 2005; Murante et al. 2004; Bell et al. 2007).

On the other hand, this large population of merging satellites has raised the question of whether mergers are *too* common in the CDM scenario. Some studies have questioned whether CDM models can produce a large enough population of "bulgeless" discs (or systems with very low bulge-to-total ratios, $B/T \lesssim 0.2$) (e.g. Graham & Worley 2008; Weinzirl et al. 2009) and whether thin, dynamically fragile discs such as the one observed in the Milky Way can survive this bombardment by incoming satellites (e.g. Toth & Ostriker 1992; Quinn et al. 1993; Walker et al. 1996; Wyse 2001; Bournaud et al. 2007). Clearly, there are three main aspects to settling this question: first, we must understand the statistics of galaxy mass accretion and merger histories in a CDM universe; second, we need to understand the physics of how galaxies are transformed by mergers with various mass ratios, orbits, and other parameters; and finally, we need accurate and unbiased statistics for the observed populations of the relevant objects (cf. Kormendy & Fisher 2008).

The availability of large, high-resolution N-body simulations has made progress possible on the first of these aspects. For example, Stewart et al. (2008) recently carried out a detailed study of statistics of merger events in galaxy-sized dark matter haloes. They confirmed previous results based on semi-analytic methods (Purcell et al. 2007; Zentner 2007), finding that the majority of the mass delivery into a dark matter halo of mass M_h is due to systems with masses $M_{\rm sat} = (0.03 - 0.3)M_h$. They also found that a large fraction (95%) of Milky-Way sized haloes have accreted a satellite with a virial mass comparable with the total mass of the Milky Way disc and approximately 70% have accreted an object with more than twice this mass since $z \sim 1$.

There have been numerous studies based on collisionless simulations that have tried to quantify the effects of these minor mergers on the thickness and stability of stellar discs (e.g. Velazquez & White 1999; Font et al. 2001; Benson et al. 2004; Gauthier et al. 2006; Kazantzidis et al. 2008, 2009; Villalobos & Helmi 2008). This work has demonstrated that the answer depends quite sensitively on the mass ratio of the satellite to the primary; there seems to be a consensus that the main danger to thin discs is not from the ubiquitous mergers with very small mass ratios (less than $\sim$ 1:10) but rather from the rarer, yet still frequent, events with larger mass ratio ($\gtrsim$1:10). For example Kazantzidis et al. (2008) studied the effects of mergers with $(0.2 - 1)M_{\rm disc}$ and concluded that thin discs could survive such mergers. Employing dissipationless simulations, Purcell et al. (2009, P09) studied the response of a fully formed Milky Way-like stellar disc within a $\sim 10^{12} M_\odot$ DM halo to mergers involving satellites with a total mass $M_{\rm sat} \sim 10^{11} M_\odot \simeq 3\, M_{\rm disc}$. They came to the conclusion that regardless of the orbital configuration of the merger these events transform the discs into structures that are roughly three times thicker than the observed thin disc component of the Milky Way.

On the observational side, there is a general consensus that $\sim$70% of Milky-Way-mass ($\sim 10^{12} M_\odot$) haloes host a disc dominated, late type galaxy (Weinmann et al. 2006; van den Bosch et al. 2007; Choi et al. 2007; Park et al. 2007). While it is also well known that the majority of the mass in the disc of our Milky Way resides in a thin component (e.g. Jurić et al. 2008), how typical this situation is for other disc galaxies in the Milky Way's mass range is less certain. Quantifying the vertical thickness of the discs of external galaxies has been attempted in a few studies (e.g. Schwarzkopf & Dettmar 2000; Yoachim & Dalcanton 2006), but is challenging because of small sample sizes, inclination effects and extinction.

P09 suggested two possible explanations for the existence of a thin disc in our Galaxy: one possibility is that the Milky Way is not a representative case and that perhaps it has had an unusually quiet accretion history for a halo of its mass. A second explanation is related to the fact that all the numerical studies performed so far have only considered the dissipationless components in the galaxy (dark matter and stars), neglecting the presence of a dissipative gas component in the disc. However, the inclusion of gas physics is known to play an important role in stabilizing galactic discs. Numerical simulations have shown that gas is important for the survivability and the regrowth of stellar discs during major mergers (Barnes 2002; Springel & Hernquist 2005; Robertson et al. 2006; Naab et al. 2006; Scannapieco et al. 2009; Governato et al. 2009), and that the presence of gas in disc-type merger progenitors greatly suppresses the formation of a post-merger spheroidal component Hopkins et al. (2009a,b). It is reasonable to expect that the presence of gas in the progenitor disc could also have an impact on the efficiency of the disc heating and thickening: gas may be able to absorb some of the kinetic impact energy of the merging satellite, and then radiate this energy away by cooling; or, gas may be able to cool and reform a new thin disc after the merger, forcing heated stars to contract again onto the disc plane.

The main goal of this paper is to study in detail how the presence of a dissipational gas component affects disc thickening in minor mergers. For the first time, we address this problem using a suite of high-resolution, fully hydrodynamical numerical merger simulations, run with the Smoothed Particle Hydrodynamics (SPH) code GADGET-2. We consider simulations with and without gas, with a variety of initial orbital parameters, and with different values of the star formation efficiency parameters. We then re-examine the issue of whether the cosmologically expected rate of minor mergers presents a problem for CDM in light of our new results and the available observations.

The remainder of the paper is organized as follows: in Section 2.1 we provide a brief summary of the GADGET-2 code and describe our simulations as well as the initial conditions for our progenitor galaxies. In Section 3 we present our main results, focusing on the difference between the dissipational and dissipationless simulations as well as on the influence of different initial conditions and star formation parameters on the final thickness of the disc. Finally in Section 4 we summarize and discuss our results, compare them with observations, and present our conclusions regarding the issue of thin disc survival in a CDM universe.

Table 1. Parameters kept constant for all simulations. Masses are in units of $10^{10} M_\odot$; scale and softening lengths are in units of kpc and pc respectively.

System	$M_{\rm vir}$	$M_{\rm disc}$	$M_{\rm b}$	$r_{\rm d}$	$r_{\rm b}$	c	$N_{\rm halo}$	$N_{\rm disc}$	$N_{\rm bulge}$	$\epsilon_{\rm DM}$	$\epsilon_{\rm disc}$
Primary	100	2.4	0.600	3.0	0.5	9.65	4 000 000	1 000 000	500 000	100	50
Sat	10	0.0	0.063	0.0	0.3	11.98	900 000	0	100 000	100	50

2 NUMERICAL SIMULATIONS

2.1 Numerical Code

We make use of the parallel TreeSPH-code GADGET-2 (Springel 2005) in this work. The code uses Smoothed Particle Hydrodynamics (SPH; Lucy 1977; Gingold & Monaghan 1977; Monaghan 1992) to evolve the gas using an entropy conserving scheme (Springel & Hernquist 2002). Radiative cooling is implemented for a primordial mixture of hydrogen and helium following Katz et al. (1996) and a spatially uniform time-independent local UV background in the optically thin limit (Haardt & Madau 1996) is included.

The SPH properties of the gas particles are averaged over the standard GADGET-2 kernel using ~ 64 SPH particles. Additionally the minimum SPH smoothing length is required to be equal to the gravitational softening length in order to prevent artificial stabilization of small gas clumps at low resolution (Bate & Burkert 1997). All simulations have been performed with a high force accuracy of $\alpha_{\rm force} = 0.005$ and a time integration accuracy of $\eta_{\rm acc} = 0.02$ (for further details see Springel 2005).

Star formation and the associated heating by supernovae (SN) is modelled following the sub-resolution multiphase ISM model described in Springel & Hernquist (2003). The ISM in the model is treated as a two-phase medium with cold clouds embedded in a hot component at pressure equilibrium. Cold clouds form stars in dense ($\rho > \rho_{\rm th}$) regions on a timescale chosen to match observations (Kennicutt 1998). The threshold density $\rho_{\rm th}$ is determined self-consistently by demanding that the equation of state (EOS) is continuous at the onset of star formation. We do not include SN-driven galactic winds nor feedback from accreting black holes (AGN feedback) in our simulations.

In our "fiducial" runs, we adopt the standard parameters for the multiphase feedback model in order to match the Kennicutt Law as specified in Springel & Hernquist (2003). The star formation timescale is set to $t_*^0 = 2.1$ Gyr, the cloud evaporation parameter to $A_0 = 1000$ and the SN "temperature" to $T_{\rm SN} = 10^8$ K. In order to test whether the values of these (uncertain) parameters affect our results, we reran two simulations with parameters that are a factor of 4 larger ($t_*^0 = 8.4$ Gyr, $A_0 = 4000$, $T_{\rm SN} = 4 \times 10^8$ K). As Springel et al. (2005) noted, this choice of parameters results in a star formation rate (SFR) of $\sim 1\ M_\odot\ {\rm yr}^{-1}$ for a Milky Way-like galaxy and gives better agreement with the long gas consumption timescale inferred for the Milky Way. However, these parameters yield a SFR that lies slightly below the Kennicutt Law.

2.2 Galaxy Models

We apply the method described in Springel et al. (2005) to construct both the central galaxy (called the primary hereafter) and the merging satellite systems. Each primary system consists of gas and stellar discs with radial profiles described by an exponential, with masses $M_{\rm gas}$ and $M_{\rm disc}$, and a spherical bulge of mass $M_{\rm b}$ embedded in a dark matter halo of mass $M_{\rm vir}$. The halo has a Hernquist (1990) profile with a scale radius a corresponding to a Navarro-Frenk-White halo (NFW; Navarro et al. 1997) with a scale length of $r_{\rm s}$ and a concentration parameter $c = r_{\rm vir}/r_{\rm s}$. We use the results of Macciò et al. (2008) to compute halo concentration as a function of virial mass.

The scale lengths $r_{\rm d}$ of the exponential gaseous and stellar discs are assumed to be equal, and are determined using the model of Mo et al. (1998), assuming that the fractional angular momentum of the total disc $j_{\rm d} = (J_{\rm gas} + J_{\rm disc})/J_{\rm vir}$ is equal to the global disc mass fraction $m_{\rm d} = (M_{\rm gas} + M_{\rm disc})/M_{\rm vir}$ for a constant halo spin λ . This is equivalent to assuming that the specific angular momentum of the material that forms the disc is the same as that of the initial dark matter halo, and is conserved during the process of disc formation.

The vertical structure of the stellar disc is described by a radially independent sech^2 profile with a scale height z_0, and the vertical velocity dispersion is set equal to the radial velocity dispersion. The vertical structure of the gaseous disc is computed self-consistently as a function of the surface density by requiring a balance of the galactic potential and the pressure given by the EOS. The stellar bulge is constructed using the Hernquist (1990) profile with a scale length $r_{\rm b}$.

Satellite systems are constructed using the same method adopted for primary systems but they consist only of a dark matter halo and a stellar bulge; neither stellar nor gaseous discs are included.

2.3 Simulation Parameters

We construct a set of primary systems, each with a virial mass of $M_{\rm vir} = 10^{12} M_\odot$ containing a disc and a bulge, and a satellite system with a virial mass of $M_{\rm vir} = 10^{11} M_\odot$ containing only a bulge. Since we wish to study a *typical* galaxy in a $M_{\rm vir} = 10^{12} M_\odot$ halo, rather than use the specific parameters of the Milky Way, we use the average stellar-to-halo mass ratio derived by Moster et al. (2009) to compute the stellar mass of every system (both primaries and satellites). The Moster et al. (2009) constraints were derived empirically by asking how the population of dark matter haloes and sub-haloes predicted by CDM must be populated with galaxies in order to reproduce the observed galaxy stellar mass function, and are in excellent agreement with con-

Table 2. Parameters for the different simulation runs. Masses are in units of $10^{10} M_\odot$, and scale height and softening lengths are in units of kpc and pc respectively. The star formation timescale (t_*^0) is expressed in Gyr. The first three entries are for isolated galaxies, and the remainder are for mergers.

Run	$f_{\rm gas}$	$M_{\rm gas}$	$M_{\rm d}$	$N_{\rm gas}$	$\epsilon_{\rm gas}$	λ	z_0	θ	t_*^0	A_0	$T_{\rm SN}$
IA	0.0	0.0	2.4	0	0	0.033	0.40	-	2.1	1000	1×10^8K
IB	0.2	0.6	3.0	125 000	70	0.034	0.40	-	2.1	1000	1×10^8K
IC	0.4	1.6	4.0	333 333	70	0.036	0.40	-	2.1	1000	1×10^8K
MA60	0.0	0.0	2.4	0	0	0.033	0.40	60°	2.1	1000	1×10^8K
MB60	0.2	0.6	3.0	125 000	70	0.034	0.40	60°	2.1	1000	1×10^8K
MC60	0.4	1.6	4.0	333 333	70	0.036	0.40	60°	2.1	1000	1×10^8K
MA45	0.0	0.0	2.4	0	0	0.033	0.40	45°	2.1	1000	1×10^8K
MB45	0.2	0.6	3.0	125 000	70	0.034	0.40	45°	2.1	1000	1×10^8K
MA30	0.0	0.0	2.4	0	0	0.033	0.40	30°	2.1	1000	1×10^8K
MB30	0.2	0.6	3.0	125 000	70	0.034	0.40	30°	2.1	1000	1×10^8K
MA60T	0.0	0.0	2.4	0	0	0.033	0.25	60°	2.1	1000	1×10^8K
MB60T	0.2	0.6	3.0	125 000	70	0.034	0.25	60°	2.1	1000	1×10^8K
MB60S	0.2	0.6	3.0	125 000	70	0.034	0.40	60°	8.4	4000	4×10^8K
MB60TS	0.2	0.6	3.0	125 000	70	0.034	0.25	60°	8.4	4000	4×10^8K

straints from other methods such as galaxy clustering, satellite kinematics and weak lensing. Note that the stellar mass we get for a typical galaxy in a $M_{\rm vir} = 10^{12} M_\odot$ halo is significantly less than what is found for the Milky Way and M31 (cf. Klypin et al. 2002).

All primary systems have a concentration parameter of $c = 9.65$ and a stellar mass of $M_{*,\rm pri} = 3 \times 10^{10} M_\odot$. Distributing 80% of this stellar mass into the exponential disc yields a stellar disc mass of $M_{\rm disc} = 2.4 \times 10^{10} M_\odot$ and a bulge mass of $M_{\rm b,pri} = 6 \times 10^9 M_\odot$. We assume a bulge scale length of $r_{\rm b,pri} = 0.5$ kpc.

For models that also include a gaseous disc component we add $M_{\rm gas,20\%} = 0.6 \times 10^{10} M_\odot$ and $M_{\rm gas,40\%} = 1.6 \times 10^{10} M_\odot$ such that the gas fraction in the disc is 20% and 40% in the two cases (cf. Stewart et al. 2009). The total disc mass is then $M_{\rm d,0\%} = 2.4 \times 10^{10} M_\odot$, $M_{\rm d,20\%} = 3.0 \times 10^{10} M_\odot$ and $M_{\rm d,40\%} = 4.0 \times 10^{10} M_\odot$ for a gas fraction of 0%, 20% and 40% respectively. We decided to keep the total stellar mass constant in order to have a more direct comparison between the dissipational and dissipationless cases. We fix the disc scale radius at $r_{\rm d} = 3.0$ kpc for all primary galaxies; because in the Mo et al. (1998) model, $r_{\rm d}$ depends on the disc mass and on the halo spin parameter, we have choosen λ in each case such that this value of $r_{\rm d}$ is obtained in all primary systems. The corresponding spin parameters are $\lambda_{0\%} = 0.033$, $\lambda_{20\%} = 0.034$ and $\lambda_{40\%} = 0.036$. We consider two cases for the initial disc scale height: we adopt a "fiducial" value of $z_0 = 0.4$ kpc for direct comparison with P09, and also consider an initially thinner disc with $z_0 = 0.25$ kpc for two values of the gas fraction (0% and 20%). Edge-on surface brightness maps for the initial conditions of our primary galaxies are shown in the upper and lower left panels of Figure 1 for $z_0 = 0.4$ and 0.25 kpc, respectively.

The satellite systems consist only of a dark matter halo and a stellar bulge. The concentration parameter of the satellite halo is $c = 11.98$. Using the stellar-to-halo mass ratio we derive a stellar mass of $M_{\rm b,sat} = 6.3 \times 10^8 M_\odot$. We set the scale length of the bulge to $r_{\rm b,sat} = 0.3$ kpc.

The primary systems always contain $N_{\rm dm} = 4 \times 10^6$ dark matter, $N_{\rm disc} = 10^6$ stellar disc and $N_{\rm bulge} = 5 \times 10^5$ bulge particles. Models with 20% and 40% gas fractions contain $N_{\rm gas,20\%} = 1.25 \times 10^5$ and $N_{\rm gas,40\%} = 3.33 \times 10^5$ gas particles, respectively. The satellite system consists of $N_{\rm dm} = 9 \times 10^5$ dark matter and $N_{\rm bulge} = 10^5$ bulge particles. We set the gravitational softening lengths to $\epsilon = 50$ pc, 70 pc and 100 pc for stellar, gas and dark matter particles, respectively.

Following P09 we choose orbits which are motivated by studies of substructure accretion in cosmological N-body simulations. The most likely values of the radial and tangential velocity components (v_r and v_t) are found to be respectively at 90% and 60% of the virial velocity of the primary halo (Benson 2005; Khochfar & Burkert 2006). For a halo of mass $M_{\rm vir} = 10^{12} M_\odot$ the virial velocity is $v_{\rm vir} = 129\,{\rm km\,s^{-1}}$ which results in an initial subhalo velocity with $v_r = 116\,{\rm km\,s^{-1}}$ and $v_t = 77\,{\rm km\,s^{-1}}$. The initial separation of the galaxies was chosen to be relatively large, $d_{\rm start} = 120$ kpc, in order to prevent significant perturbations of the disc due to the sudden presence of the satellite's gravitational pull. Once $d_{\rm start}$ is chosen, the orbital parameters are uniquely determined. This, of course, limits our study to a single cosmologically motivated orbit. Our combination of initial velocity and distance fixes the pericentric distance at ~ 18 kpc. We use a set of three orbital inclinations ($\theta = 60°$, 45° and 30°, where θ is the angle between the spin axes of the disc and the orbit) to investigate the effect of the inclination on the rate of thickening of the disc. All orbits are prograde and all simulations were evolved for a total of 6 Gyr. Prograde orbits are expected to be more destructive to the disc than retrograde mergers (Velazquez & White 1999).

We summarize the parameters that are kept constant for all simulations in Table 1, and parameters that differ

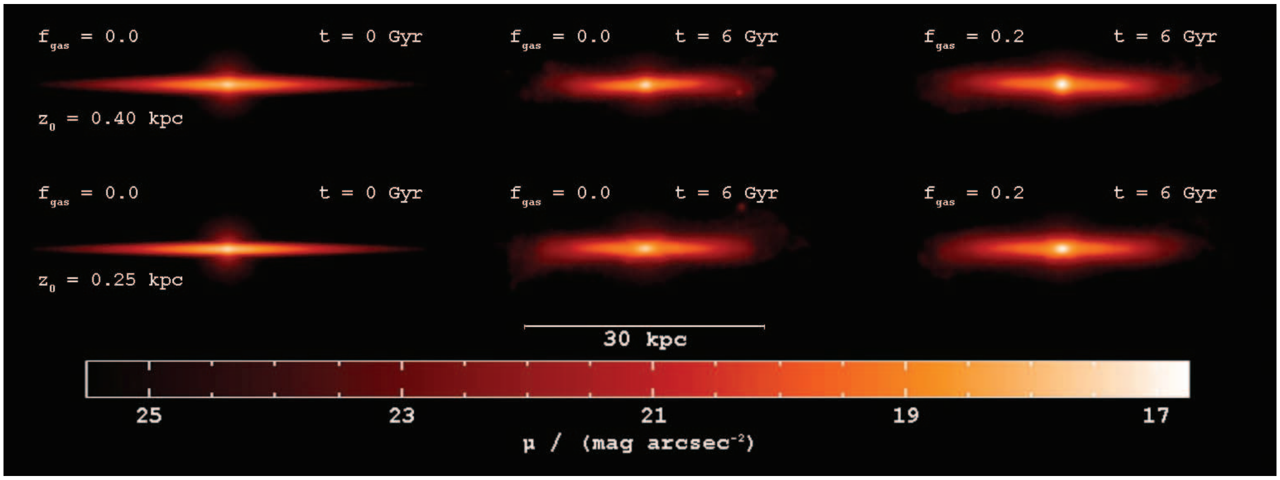

Figure 1. Edge-on surface brightness maps for galaxies with an initial scale height of $z_0 = 0.40$ kpc (upper row) and $z_0 = 0.25$ kpc (lower row). The left column shows the initial models while the centre and the right columns show the final galaxies (t=6 Gyr) for an initial gas fraction of 0% and 20%, respectively. A mass-to-light ratio of 3 $(M/L)_\odot$ has been assumed, typical of the Milky Way in the B-band.

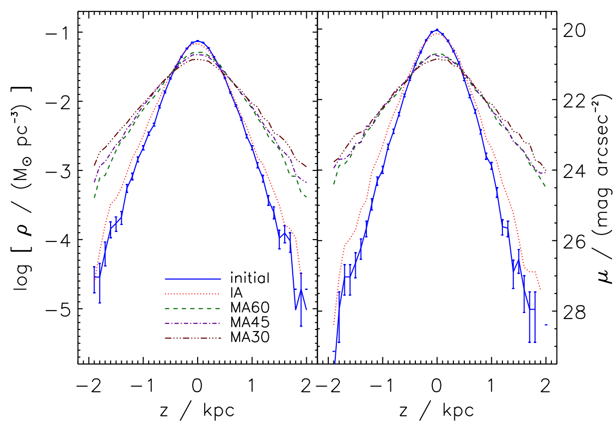

Figure 2. Density profiles for the initial ($z_0 = 0.4$ kpc) and final discs for an isolated galaxy and mergers with three inclination angles, for the simulations with no gas. The left panel shows the stellar mass density as a function of the distance to the galactic plane at a radius of 8 kpc. The right panel shows the edge-on projected surface brightness at a projected radius of 8 kpc.

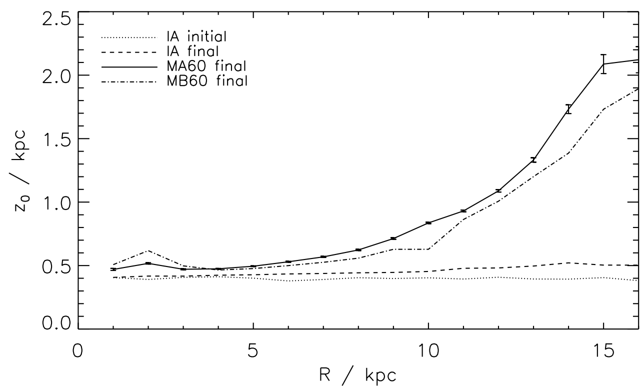

Figure 3. Disc scale height derived from fitting to the stellar mass density at different radii, for the initial (dotted line) and final states of a an isolated galaxy (IA; dashed line) and for a merger without gas (MA60, solid line) and with 20% gas (MB60; dot-dashed line), both for an inclination of 60°.

for the various simulation runs are summarized in Table 2. We label the different simulations with the first letter I for isolated runs and an M for mergers. The second letter signifies the gas fraction of the disc followed by a number signifying the orbital inclination. We add a T for discs with an initial scale height of $z_0 = 0.25$ and an S for simulations with a lower star formation efficiency. We adopt a gas fraction-inclination combination of 20% and 60° as our fiducial model.

3 RESULTS

In order to study the evolution of the disc we compute the stellar mass density as a function of the distance to the galactic plane at a distance of $R_\odot \sim 8$ kpc from the disc spin axis. Figure 2 shows density profiles for a set of simulations that do not contain any gas. In the left panel, stellar mass density profiles of the initial disc (with $z_0 = 0.4$ kpc) and the final discs for an isolated galaxy and mergers with three inclination angles are plotted. To compare simulations to observations we also compute the edge-on projected surface brightness as a function of the distance to the galactic plane at a radius of $R_\odot$. This is done by taking a vertical slice at a distance of $R_\odot$ to the galactic centre and assuming a mass-to-light ratio of $M/L = 3(M/L)_\odot$, appropriate for the Milky Way in the B-band (Zibetti et al. 2009). In the right panel of Figure 2, the edge-on surface brightness profiles are shown for the same simulations. As is clearly visible from both panels, the disc of the isolated galaxy is stable over the duration of the simulation, while during mergers the profiles clearly broaden, implying that the disc becomes thicker.

We note that the projected edge-on surface density profiles are thicker than the “slices” through the 3d mass density profiles. To understand this we plot the disc scale heights derived by fitting to the 3d stellar mass density slices at different radii in Figure 3. This shows that z_0 increases with increasing distance from the galaxy center. When computing

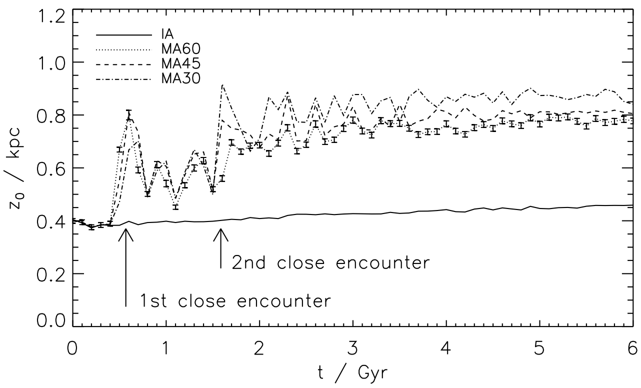

Figure 4. Evolution of the disc scale height for simulations with no gas. The solid line shows the scale height of an isolated galaxy while the other lines illustrate mergers with different inclinations.

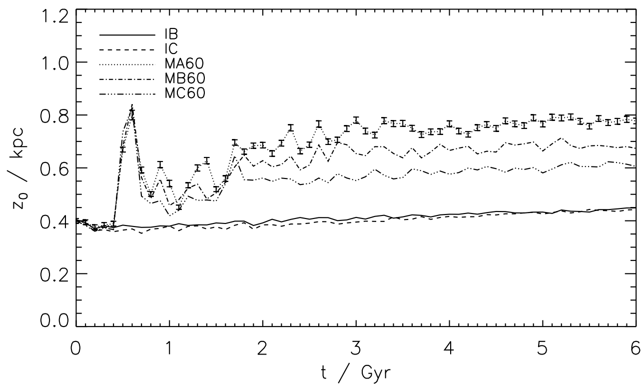

Figure 5. Evolution of the disc scale height for simulations with gas. The solid and the dashed lines show the isolated case while the other lines illustrate mergers with different gas fractions (0%, 20% and 40% for MA60, MB60 and MC60, respectively).

the projected edge-on surface density profiles, stellar particles with a larger distance from the galactic centre than the specified radius are naturally included, since some of these particles happen to lie along the line of sight. These particles are on average also more distant from the galactic plane, as Figure 3 indicates. This results in an apparently thicker edge-on surface density profile and a larger projected disc scale height. In order to compare our results with observations we use the scale height obtained by fitting to the projected edge-on surface density profile in the following.

3.1 Stability of the Initial Conditions and Evolution of the scale height

Galactic discs are fragile systems and there is always the possibility that purely numerical effects can modify their morphology, e.g. through bar formation or flaring. The stability of the initial disc is then a key point to be addressed before looking at the effects of satellite mergers. To quantify the amount of disc thickening we fit for the value of z_0 assuming a sech^2 profile. We always fit to the projected edge-on surface brightness profile at $R_\odot$ as discussed above.

The dotted and dashed lines in Figure 3 show the values of the disc scale height as a function of radius for an isolated galaxy (IA) at $t = 0$ and $t = 6$ Gyr, respectively. The final disc does not develop any appreciable flaring and the thickening at larger distances is negligible compared to the thickening due to satellite accretion events. In Figure 4 we show the resulting time evolution of z_0 for an isolated galaxy and mergers with varying inclinations, all containing no gas. The isolated case (solid line) shows that in the absence of perturbations the thin disc is extremely stable during the 6 Gyr timescale over which we run the simulations. This is also true for the isolated runs including a gas component (IB and IC) as the solid and dashed lines in Figure 5 show. This implies that any increase in z_0 is due to accretion events. We see that regardless of the inclination of the orbit, the disc thickens significantly in the merger simulations, with z_0 increasing by a factor of ~ 2.

We note that we also ran a simulation of an isolated galaxy using one fourth the number of particles of our fiducial case (in all species) and find that the scale height increases by 50%. This demonstrates the importance of numerical resolution in determining the disc stability.

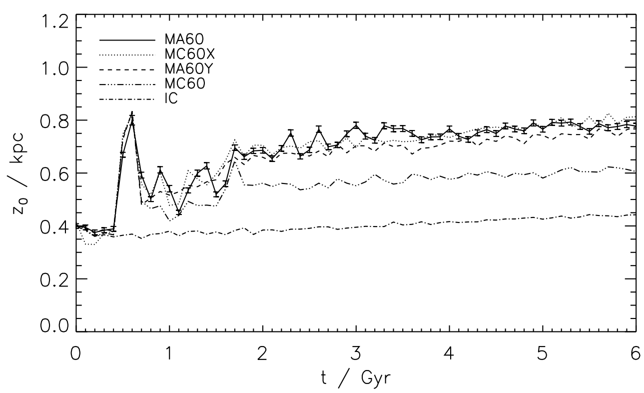

Figure 6. Evolution of the disc scale height for simulations without gas but with a more massive disc. The dotted lines shows the result for a simulation with an additional collisionless disc having the same mass and distribution as the gas disc in MC60. The dashed line shows the result of a simulation containing one stellar disc with increased mass (equal to the total baryonic mass in MC60). The solid and dot-dashed lines indicate the reference cases (MA60, MC60, IC). We see that the presence of dissipational gas, not the more massive disc, is responsible for the reduction in disc thickening.

3.2 The effect of gas in the disc

All of the previous numerical experiments devoted to studying the heating and thickening of stellar discs by minor mergers have included only the dissipationless components of the galaxies: dark matter and stars. The presence of a gaseous component in the disc, which requires a hydrodynamical approach to the problem instead of a purely gravitational one, has been neglected so far. The presence of gas may suppress disc thickening in two ways. One possibility is that the gas may absorb some of the kinetic impact energy of the merging satellite, which can then be removed from the system by radiative cooling. In this way the impact energy that is transferred to the stars, causing heating and thickening, may be reduced. Another possible mechanism is that gas forms a new thin stellar disc after the merger. This disc could then cause the heated stars to contract towards the disc plane.

We analyze the surface brightness profiles of the merger simulations with gas, and show the resulting evolution of the scale height in Figure 5 for initial gas fractions of 0%,

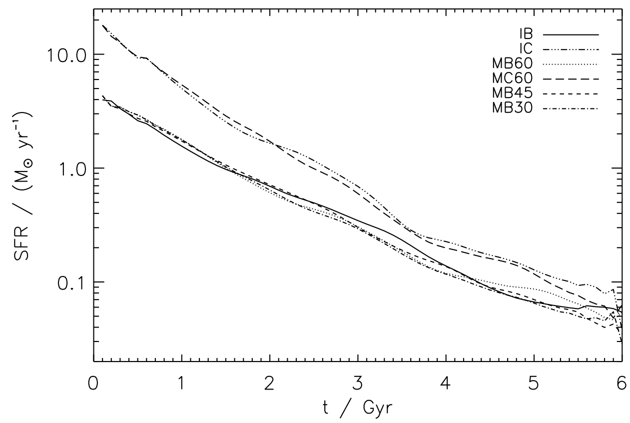

Figure 7. Star formation rates for isolated galaxies and mergers, with initial gas fractions of 20% (IB, MB60, MB45, MB30) and 40% (IC, MC60) in the progenitor disc.

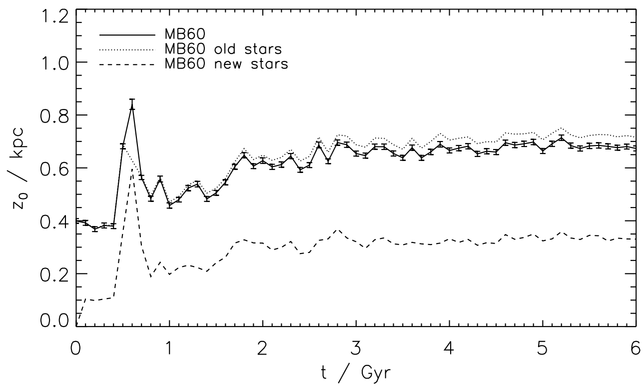

Figure 8. Evolution of the disc scale height for old stars (created in the initial conditions) and new stars (created during the simulation through star formation). The scale height for the combined sample is also shown for comparion.

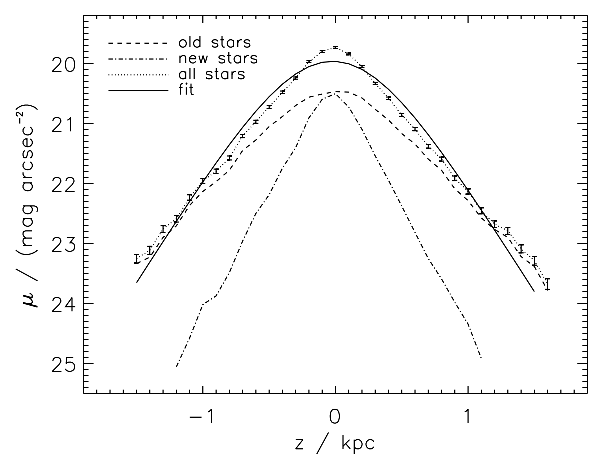

Figure 9. Final edge-on projected surface brightness profile for the 40% gas case at a projected radius of 8 kpc for old, new and all stars. The solid line shows the fit to the combined stellar disc profile.

20% and 40%, and an inclination of 60° (MA60, MB60 and MC60). This shows that the presence of gas does indeed suppress the thickening of the disc by a minor merger. The final scale height increases by a factor of ~ 1.75 for the 20% gas case, and by only a factor of 1.5 for the 40% gas case, in contrast to the factor of 2 increase in the gas-free case (corresponding to a decrease in the final scale height of 25% and 50%, respectively).

One might wonder whether the reduced thickening is due to the additional potential of the gas particles. In order to investigate whether the gas physics or the greater potential have a larger impact on the suppression of the disc thickening, we ran two additional collisionless simulations. For the first simulation we use the initial conditions of MC60 and convert all gas particles to stellar particles at $t = 0$ Gyr (MC60X). We thus get an additional stellar disc which has the same profile and potential as the previous gaseous disc, but behaves collisionlessly during the simulation. In a second simulation we create a galaxy like MA60 but increase the mass of the stellar disc to $M_{\rm disc} = 4.0 \times 10^{10} M_{\odot}$ (MA60Y). This galaxy has the same disc mass as MC60 and MC60X. Figure 6 shows that in both collisionless simulations (MC60X and MA60Y) the disc scale height increases by a factor of ~ 2. The final scale heights are equal or even larger than for the less massive galaxy without gas (MA60). This demonstrates that the suppression of the thickening in the runs including gas is not due to the additional potential of the gas disc but lies in the hydrodynamical nature of the particles.

In order to gain insights into the physical process that is causing this change in behaviour, we examine the SFR as a function of time. The results are shown in Figure 7. The galaxy with a gas fraction of 40% (IC and MC60) naturally starts with a high SFR ($\sim 18\ M_{\odot}\ {\rm yr}^{-1}$), while the galaxy with a gas fraction of 20% (IB, MB60, MB45 and MB30) starts with a lower SFR of $\sim 4\ M_{\odot}\ {\rm yr}^{-1}$. We see that 1:10 mergers do not have a noticable impact on the SFR.

The SFR quickly drops to low values under $1\ M_{\odot}\ {\rm yr}^{-1}$ (after 2.5 Gyr for a gas fraction of 40% and 1.5 Gyr for the gas fraction of 20%). This implies that most of the gas is consumed before the merger is complete. Thus, the galaxy is not able to reform a new thin stellar disc after the merger, which could pull heated stars towards the galactic plane again. This means that the dominant process preventing disc heating in the simulations above is the absorption of the kinetic impact energy of the satellite by the gas component. This can also be directly inferred from Figure 5: from about 2 Gyr, one can see that the growth of the scale height z_0 is slower in the simulations with gas, indicating that from the beginning the gas is absorbing the impact energy and preventing the disc from thickening considerably. If the main mechanism was the reforming of a new thin disc, one would see the disc thicken and then contract again. This would mean a different slope for the z_0 time evolution in runs with different gas fractions, however, we find similar slopes for all gas fractions indicating that this process is not dominant.

Another way to demonstrate that the formation of a new disc does not reduce the disc thickening noticeably in our simulations is to compare the scale height of the stellar particles created in the initial conditions (old stars) to the scale height of the stellar particles that form during the simulation through SF (new stars). In Figure 8 we compare the evolution of z_0 for old and new stars in our fiducial case MB60. The new stars clearly form a thinner disc than the

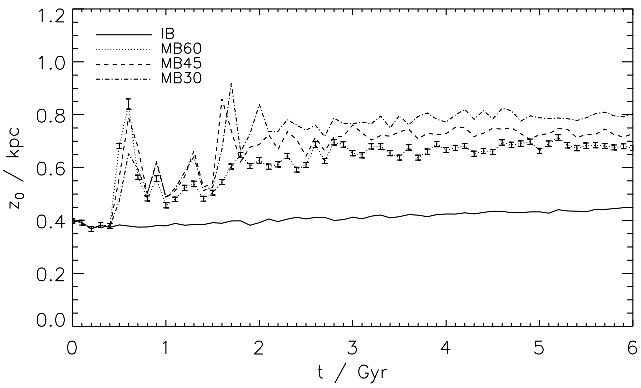

Figure 10. Evolution of the disc scale height for simulations with gas. The solid line shows the scale height of an isolated galaxy while the other lines illustrate mergers with different inclinations.

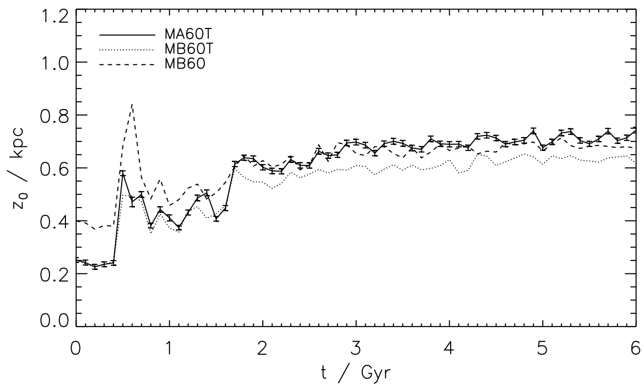

Figure 11. Evolution of the scale height for a disc with a smaller initial scale height. The solid line shows the 'thin disc' simulation without gas, the dotted line shows thin disc case with 20% gas, and the dashed line shows the 20% gas case with the original choice of initial scale height.

old stars, however, the combined sample has a scale height which is only slightly thinner than the old stellar disc. This is due to the much larger mass contained in the old stellar disc component. Figure 9 shows the resulting edge-on projected surface brightness profile for the 40% gas case at 8 kpc for old, new and all stars and a fit to the combined stellar disc using a sech^2 model. The combined profile does not show an obvious transition between the old and the new disc profile. However, one has to keep in mind that we are using a single sech^2 model to fit two distinct profiles, implying that the fitted scale height of the combined sample decreases due to the presence of the new thin disc. The new and old discs have a final scale height of 0.38 and 0.66 kpc while the total stellar disc has $z_0 = 0.61$ kpc. This shows that even for a gas fraction of 40% (which is expected for disc galaxies at $z \sim 1$ but not for local galaxies at the present time), the new thin disc is not massive enough to reduce the total disc scale height significantly. In order to form a new thin disc with a mass comparable to the old stellar disc, the SFR after the merger would have to be much higher. This could occur in the case of an extremely gas-rich initial disc ($\geqslant$ 90% gas; Robertson et al. 2006; Hopkins et al. 2008).

In order to investigate the influence of the orbital inclination on the disc thickening we compute the evolution of the scale height for mergers with gas fractions of 20% for three different orbital inclinations $\theta = 60°, 45°, 30°$(MB60, MB45, MB30 respectively). We plot the results in Figure 10. The black solid line (IB) represents the isolated case with gas (20%), which is seen to be very stable as in the no-gas case. The results for different orbital inclinations show that the value of θ has a small effect on the growth of the scale height. Regardless of the inclination, the overall increase of the scale height for simulations including gas is about 25% smaller than in the respective dissipationless simulations.

3.3 A thinner initial disc

The choice of initial scale height for our primary disc was somewhat arbitrary. In order to investigate whether a thinner initial disc would result in a thinner disc today, we simulate a merger of a disc with an initial scale height of $z_0 = 0.25$ kpc both without and with gas (20%) and an inclination of 60°. The resulting evolution of z_0 is shown in Figure 11. The final scale height of the disc without gas is as large as the scale height of the corresponding initially thicker discs. This may be due to the fact that an initially thicker disc is more robust to heating by accretion events (Kazantzidis et al. 2009). When gas is present, the final scale height is slightly smaller in the case with an initially thinner disc, but even a thinner initial disc is transformed into a system with a scale height of more than 0.6 kpc. Thus, even when the effects of gas in the progenitor disc are included, it seems to be difficult to obtain a disc with a scale height that is substantially smaller than this value following a minor (mass ratio greater than 1:10) merger.

3.4 Lower SF efficiency

In order to investigate the sensitivity of our results to the parameters chosen for star formation and SN feedback, we have run some simulations with lower star formation efficiency. In particular, we were interested to see whether adopting a lower star formation efficiency would allow a more significant new thin disc to reform following the merger. For this test we employ a star formation timescale $t_*^0 = 8.4$ Gyr, a cloud evaporation parameter $A_0 = 4000$ and a SN "temperature" $T_{\rm SN} = 4.0 \times 10^8$ K in order to have a SFR of $\sim 1\ M_\odot\ {\rm yr}^{-1}$ for a Milky Way-like Galaxy (Springel et al. 2005). We run this case for initial scale heights of $z_0 = 0.4$ kpc and $z_0 = 0.25$ kpc, in both cases using our fiducial value of a 20% gas fraction and an inclination of 60°.

We first compare the SFRs of the simulations with lowered SF efficiencies with our fiducial results. The left panel of Figure 12 shows the SFRs for the simulations MB60, MB60T, MB60S and MB60TS. As we see, the SFRs in MB60S and MB60TS are initially lower than those of MB60 and MB60T, respectively. After the merger ($t \sim 1.8$ Gyr) however, the simulations with the lower SF efficiency have a higher SFR, since MB60 and MB60T have already consumed most of their gas supply. Due to the lower SFR during the early stages of the simulation, the amount of newly formed stellar mass is still lower in MB60S and MB60TS, as can be seen in the right panel of Figure 12. This means that the thin disc consisting of new stars affects the overall disc scale height even less than in the simulations MB60 and MB60T. The resulting scale heights are plotted in Figure 13. As expected from the SFRs, the scale heights of MB60S

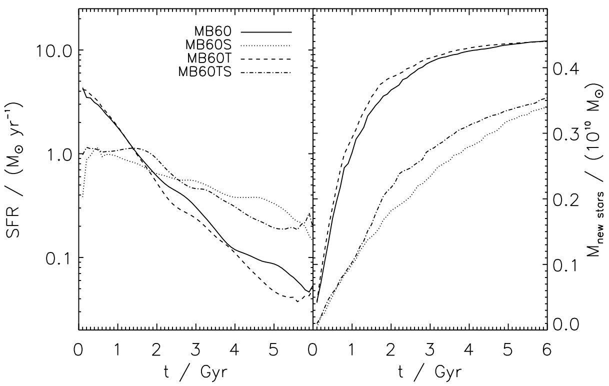

Figure 12. Left panel: SFR for simulations with the default (MB60, MB60T) and lowered SF efficiencies (MB60S, MB60TS), for the disc with initial scale height $z_0 = 0.4$ kpc and $z_0 = 0.25$ kpc (T). Right panel: Mass of stellar particles formed during the simulations.

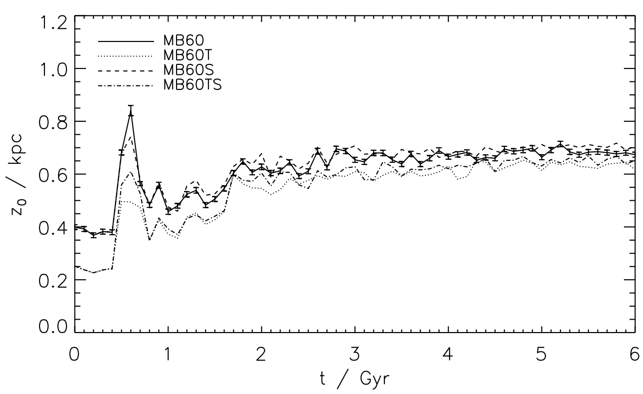

Figure 13. Evolution of the disc scale height for simulations with higher (MB60, MB60T) and lower SF efficiencies (MB60S, MB60TS).

and MB60TS are slightly larger than those of MB60 and MB60T, respectively.

Clearly, in order for the disc thickening problem to be solved by the growth of a new stellar disc following the merger, the mass of the new disc must be comparable in mass to that of the old stellar disc. This implies that a significant amount of gas must remain available at the end of the merger. Based on our results, when the SF and SN feedback parameters are tuned be consistent with the empirical Kennicutt law, most of the gas tends to be consumed during the merger. Simulations with much higher initial gas fractions ($\sim$ 90%) or which included a new source of cold gas (e.g. via cooling and accretion from a hot halo) might be able to regrow a more massive thin disc.

4 CONCLUSIONS AND DISCUSSION

We investigated the role of dissipational gas physics in the vertical heating and thickening of disc galaxies by minor mergers (mass ratio $\sim$ 1:10). We used the parallel TreeSPH-code GADGET-2 to simulate a suite of minor merger simulations for a Milky Way-like primary galaxy. The suite consists of collisionless simulations as well as runs containing gas in the disc. Using cosmologically motivated orbital parameters, we ran simulations with three different orbital inclinations (60°, 45° and 30°) and two different initial disc scale heights ($z_0 = 0.4$ kpc and $z_0 = 0.25$ kpc).

We fit for the value of the scale height z_0, assuming a sech^2 form for the vertical density profile. We showed that the scale height derived from a fit to the mass density is a strong function of the radial distance to the disc axis: as is well known, minor mergers tend to cause flaring in the outer part of the disc. This results in projected edge-on surface density profiles which appear thicker than the actual three dimensional density profiles since stars that are at a large distance from the galactic centre and thus also more distant from the galactic plane are viewed along the line of sight.

We found that in dissipationless simulations, minor mergers (without gas) caused the scale height of the disc to increase by about a factor of two, with the orbital inclination affecting the amount of thickening by only about five percent. Thus, in qualitative agreement with the results of P09, we find that in the absence of gas, cold thin discs are destroyed by minor mergers. However, it is interesting that in spite of the fact that the parameters of our simulations were chosen to be very similar to those of P09, they found that the scale height of the disc increased by a larger factor of ~ 3, leading to a final disc about twice as thick as ours (despite having the same initial scale height).

Although the discs in both simulation suites are stable against secular evolution effects, this does not necessarily ensure that both models are equally resistant to strong perturbative effects during an accretion event. Possible reasons for this discrepancy may be the use of a different IC generator and a different simulation code. The velocity dispersions for example are fixed differently; while in our ICs the radial and the vertical velocity dispersions are equal, the code used by P09 reproduces the velocity ellipsoid for the Milky Way. This may result in an initially hotter disc for our typical galaxy (for a $M_{\rm vir} = 10^{12} M_\odot$ halo) which is more resilient to massive accretion events. Other intrinsic differences in the simulations of P09 are a more massive disc (which may potentially be less stable due the formation of a bar) and a larger stellar mass of the satellite (which results in a larger gravitational pull each time the subhalo passes the disc). We also note that P09 use a different concentration parameter (for both the primary halo and the subhalo) and chose a Sersic profile for the bulge and an NFW profile for the halo component while we use a Hernquist profile for both components. It is not obvious which of the mentioned differences has the largest impact on the resulting disc scale heights.

We note that our results are consistent with those of Villalobos & Helmi (2008). These authors start with similar initial conditions but employ a thicker disc ($z_0 = 0.7$ kpc). The final scale heights are between 1.0 and 1.3 kpc, depending on the orbital inclination and are not as extreme as found by P09. The relative thickening is even lower than in our simulations, confirming that initially thicker discs are more robust to accretion events.

We also investigated mergers in which the progenitor disc initially contained a gas fraction of 20 or 40 %. We found that the presence of gas reduces the final scale heights by 25% (50%) for a gas fraction of 20% (40%). The final scale heights were between 0.6 and 0.7 kpc (1.5 to 1.75 times larger than the initial value), depending on the initial gas fraction and the orbital inclination. We argued that the presence of gas can have an impact on disc thickening via two

different mechanisms. One process is the absorption of kinetic impact energy by the gas. This energy can then be dissipated via radiation. Another possible effect is the formation of a new thin disc, which can cause heated stars to recontract towards the disc plane. We showed that in our simulations, in which the SF and SN feedback parameters were set to be consistent with the empirical Kennicutt law for the initial disc, most of the gas is consumed during the merger, and therefore the regrowth of new thin discs has a negligible impact on the mass-weighted scale height of the post-merger galaxy. Therefore, it seems that the main process that suppresses disc thickening in the presence of gas in our simulations is the absorption of impact energy by the gas. We intend to investigate the details of the physics of this process in more detail in future work.

We computed scale heights for old stars (i.e. stellar particles that were present in the initial conditions) and for new stars (stellar particles created during the simulation through SF). The scale height for old stars was found to be slightly higher than the overall value (~ 0.73 kpc vs ~ 0.67 for our fiducial case of 20% gas and a 60° inclination) while the scale height of the new stars was about half of that value (~ 0.35 kpc). We showed that the final mass of the new disc is small compared to that of the old disc. This indicates that although a new thin disc does form, it does not have a significant effect on the final thickness of the total disc. We argue that in order to have a noticeable effect, the new thin disc would need to be comparable in mass to the old disc, which would require that a significant mass of cold gas is still present at the end of the merger.

We ran simulations with two different initial scale heights, $z_0 = 0.40$ kpc (fiducial case) and $z_0 = 0.25$ kpc (thin). As it turns out, thinner discs are more unstable to heating and are therefore thickened more by the merger than initially thicker discs. As a result, the two cases result in discs with nearly the same final scale height (~ 0.6 kpc for the 20% gas fiducial case).

To study the sensitivity of our results to the parameters controlling SF and SN feedback, we ran simulations with a lower star formation efficiency. In these simulations, less gas is consumed and so the SFR at the end of the merger is higher. However, we found that the final mass of the new disc was still lower than in the simulations with the higher SF efficiency. This results in final scale heights that are slightly larger than in the fiducial case. We conclude that in order to reform a new thin disc comparable in mass to the old disc, either the initial gas fraction would have to be much higher, or an external fueling reservoir (such as cooling and accretion from a hot halo) would be needed (Sommer-Larsen et al. 2003; Kaufmann et al. 2006; Peek 2009; Grcevich & Putman 2009)

In light of our results, we can now reassess whether disc thickening by minor mergers presents a serious problem for CDM. First, we need to compare the fraction of disc galaxies that are expected to have had a minor merger (mass ratio greater than 1:10 but less than about 1:4) since $z \sim 1$ with the fraction of observed galaxies with thin discs. Observations show that roughly 70% of Milky Way-sized haloes host late-type galaxies (Weinmann et al. 2006; van den Bosch et al. 2007). Based on an analysis of cosmological simulations, Stewart et al. (2008) find that 20% of Galaxy-sized haloes did not experience any merger event of 1:10 or larger in the past 8 Gyr. This implies that 30% of all Milky Way-like galaxies did not have such a merger, and as a result can be expected to have retained their thin disc. This means that if less than 30% of all Milky Way-like galaxies are found to have scale heights that are substantially lower than those found in our simulations (~ 0.6 kpc) then there is no discrepancy.

Obtaining statistically unbiased observational measurements of scale heights for a complete sample of galaxies is difficult, due to small sample sizes, dust extinction, and inclination effects. Still there have been many studies focusing on the vertical structure of galaxies (e.g. Shaw & Gilmore 1989, 1990; de Grijs & van der Kruit 1996; de Grijs et al. 1997; Pohlen et al. 2000; Kregel et al. 2002; Bizyaev & Kajsin 2004). All these studies suggest that the majority of observed galaxies with properties similar to those of the Milky Way have sech^2 scale heights in the range of $0.6 < z_0 < 1.0$ kpc with a ratio between scale height and scale length between 0.2 and 0.3. These values have been determined from observed two-dimensional surface brightness profiles. Usually it is assumed that scale length and scale height are independent parameters. A model 2d surface brightness profile consisting of an exponential radial factor and a vertical factor (sech^2, sech or exp) is then fitted to the observed 2d profile. All scale heights cited here have been converted to a sech^2 profile.

A statistical study of the vertical structure of spiral galaxies is presented in Schwarzkopf & Dettmar (2000). They found that the majority ($\sim 60\%$) of galaxies have vertical scale heights less than 1.1 kpc, with a maximum between 0.4 kpc $\leqslant z_0 \leqslant$ 0.8 kpc, while galaxies with a very thin disc ($z_0 < 0.4$ kpc) are extremely rare. Similar results were obtained by Yoachim & Dalcanton (2006), who derived scale heights for a sample of edge-on galaxies and presented a relation between scale height and circular velocity. They showed that Galaxy-sized systems are expected to have scale heights in the range 0.6 kpc $\leqslant z_0 \leqslant$ 1.2 kpc. In order to compare our results to these studies, we compute 2d edge-on disc surface brightness profiles (as shown in Figure 1) and fit a model 2d profile consisting of an exponential radial and sech^2 vertical disc to the simulated profiles. For the collisionless fiducial run MA60 the final scale height is 0.74 kpc, while for the fiducial runs including a gas disc MB60 and MC60 the scale heights are 0.66 and 0.62 kpc, respectively. These values fall precisely in the observed range.

Previous theoretical studies, such as P09, have focussed on whether the observed scale height of the Milky Way is in conflict with the predictions of CDM models. We revisit this issue as well. There have been various studies of the vertical structure of the Milky Way (e.g. Bahcall & Soneira 1980; Kent et al. 1991; Reid & Majewski 1993; Larsen & Humphreys 2003; Jurić et al. 2008). These studies find exponential scale heights for the Milky Way's old thin disc of $h_z \sim 0.3$ kpc and for the young star forming disc of $h_z \sim 0.1$ kpc. As is standard in the literature, we convert these exponential scale heights to values corresponding to a sech^2 function using $z_0 = 2h_z$ (which yields very good agreement between the two profiles at $z \geqslant z_0$ and reasonable agreement at $z_0 > z$). This results in scale heights of $z_0 = 0.6$ kpc (old disc) and $z_0 = 0.2$ kpc (young disc). The former is just what we find for the overall scale height in our fiducial merger with gas, while the latter is very close to

what we find for the disc of new stars, as shown in Figure 8. Thus, in light of our results, even if the Milky Way did experience a recent 1:10 merger, if the disc contained even 20% gas (similar to the gas fraction today) at the time of the merger, there is no conflict with observations. Of course, it is also possible to explain the Milky Way by assuming that it is one of the 30% of systems that did not experience a 1:10 merger. It has been previously suggested by Hammer et al. (2007), based on the unusually low mass and angular momentum of the Milky Way disc, that our Galaxy may have had a particularly quiescent formation history.

We also note that while we are fitting the scale height to mass profiles, observational studies use luminosity profiles to derive z_0 . Based on the models of Bruzual & Charlot (2003) for a single age stellar population, we expect the B-band mass-to-light ratio of very young stars ($t_a < 2$ Gyr) and old stars ($t_a > 8$ Gyr) to differ by a factor of ~ 4. This implies that the new stellar particles should carry a correspondingly larger weight in a luminosity-weighted fit, resulting in a smaller estimated scale height. However, as seen in Figure 12, the mass of such young stars formed in our simulations is very small (only about a tenth of the mass of the pre-existing stellar disc), so even if we accounted for the age-dependent mass-to-light ratio, the overall measured scale height would not differ significantly from the mass-weighted one. Moreover, young stars will also tend to be more enshrouded by dust, further reducing their impact on the measured scale height.

Finally, the simulations presented here still neglect the larger scale environment and cosmological growth of the galaxy. The progenitors of Milky Way discs presumably had somewhat different properties (smaller masses, higher gas fractions, and possibly thicker discs) than their present-day counterparts. Perhaps most importantly, one expects these systems to have accreted a significant amount of new material over the course of the past 6–8 Gyr via accretion and cooling from a hot gas halo. This additional supply of cold gas to the disc could enhance the formation of a new, thin disc and further reduce the thickening by minor mergers. We plan to re-examine this problem in the context of simulations with a cosmologically motivated merger and accretion history, and including cooling from a hot halo, in a future work.

In final summary, in contrast with the conclusions reached by P09 using dissipationless simulations, we conclude that the existence of a thin disc in the Milky Way is not in obvious conflict with the predictions of the CDM model. Although the Milky Way may have had an unusually quiescent merger history, mooting the issue of disc thickening by minor mergers, our results indicate that one does not need to rely on such an argument. When we include a moderate amount of cold gas in the progenitor disc (similar to the gas fractions observed in typical spirals today), the scale heights of simulated discs that have experienced a 1:10 merger are in good agreement with the observed values both for the Milky Way thin disc and for external galaxies.

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